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8^{th} INTERNATIONAL WINTERSCHOOL ON NEW DEVELOPMENTS IN SOLID STATE PHYSICS

"Interaction and Scattering Phenomena in Nanostructures"

14 - 18 FEBRUARY, 1994
MAUTERNDORF, AUSTRIA

Programme
and
Abstracts

8th International Winterschool, Mauterndorf - Preliminary Programme

Monday, 14 Feb, 1994:

9.00	*Opening*	
9.15	**L.Eaves**	(University of Nottingham, UK)
	"Resonant Tunneling into Quantized Dots and Wires: Pitfalls and Progress"	
10.00	**B.Kramer**	(University of Hamburg, Germany)
	"Interactions in the transport properties of nanostructures"	
10.45	*Coffee Break*	
11.15 - 12.00	**J.Weis**	(Max Planck Institut, Stuttgart, Germany)
	"Transport Spectroscopy on a Single Quantum Dot in the Non-Linear Regime with and without Magnetic field"	
17.10	*Coffee*	
17.15	**Y.Imry**	(Weizmann Institute, Rehovot, Israel)
	"Dephasing of Diffusive Electrons at Low Dimension"	
17.55	**M.Read**	(Yale University, USA)
	"Low Dimensional Resonant Tunneling and Coulomb Blockade - a Comparison of Fabricated Versus Impurity Confinement"	
18.35 - 19.15	**E.Gornik**	(Technical University, Vienna, Austria)
	"FIR Emission Spectroscopy of Distribution Functions in Low Dimensional States"	

Tuesday, 15 Feb, 1994:

9.00	**K.Likharev**	(SUNY Stony Brook, USA)
	"Theory of Single-Electron Devices"	
9.45	**Th.Geisel**	(University, Frankfurt am Main, Germany)
	"Chaotic Transport and Fractal Spectra in Lateral Superlattices"	
10.30	*Coffee Break*	
11.00 - 11.45	**C.Hamaguchi**	(Osaka University, Japan)
	"Wannier-Stark Effect in Superlattices"	
17.00	*Coffee*	
17.15	**M.Grundmann**	(Technical University, Berlin, Germany)
	"One Dimensional Excitonic Recombination Kinetics and Intersubband Relaxation"	
17.50	**W.Wegscheider**	(AT&T Bell Laboratories, USA)
	"Lasing in Lower Dimensional Structures Formed by Cleaved Edge Overgrowth"	
18.35 - 19.10	**W.Hansen**	(University, Munich, Germany)
	"Spectroscopy on Field-Effect Defined Quantum Wires"	

Wednesday, 16 Feb, 1994:

9.00	**A.Pinczuk**	(AT&T Bell Laboratories, USA)
	"Inelastic Light Scattering in the Fractional Quantum Hall Regime"	
9.45	**N.Read**	(Yale University, USA)
	"Theory of the Half-Filled Landau Level"	
10.30	*Coffee Break*	
11.00 - 11.45	**H.Störmer**	(AT&T Bell Laboratories, USA)
	"Of Electrons and Flux Quanta"	
17.00	*Coffee*	

17.15	**A.Zrenner** (Schottky Institute, Munich, Germany) "Condensation of Indirect Excitons in AlAs/GaAs Coupled Quantum Well Structures"
17.55 - 18.35	**LeSi Dang** (University J.Fourier, Grenoble, France) "Optical Studies on II-VI Compound Quantum Wires and Boxes"
19.30	*Dinner (Hotel Post)*

Thursday, 17 Feb, 1994:

9.00	**P.Kocevar** (University of Graz, Austria) "Picosecond and Femtosecond Spectroscopy of Highly Excited Charge Carriers in Semiconductors: Theory"
9.45	**D.K.Ferry** (Arizona State University, Tempe, USA) "Theory of Ultrafast Phenomena in Laser Excited Semiconductors"
10.30	*Coffee Break*
11.00 - 11.45	**J.Feldmann** (University, Marburg, Germany) "Coherent Dynamics of Exciton Wave Packets"
17.00	*Coffee*
17.15	**H.Kurz** (Technical University, Aachen, Germany) "Terahertz Bloch Oscillations in Semiconductor Superlattices"
18.00	**M.Helm** (University, Linz, Austria) "Bloch- and Localized Electrons in Semiconductor Superlattices"
18.25	**H.Silberbauer** (University, Regensburg, Germany) "Magnetotransport in Antidot Superlattices: The Quantum Picture"
18.50- 19.15	**G.Hendorfer** (University, Linz, Austria) "Optical Spectroscopy on Quantum Wells and Tunnel Structures under Conservation of Angular Momentum"

Friday, 18 Feb, 1994

9.00	**B.S.Meyerson** (IBM, Yorktown Heights, USA) "UHV/CVD Growth of Si/SiGe Heterostructures and their applications"
9.40	**J.Olajos** (University of Lund, Sweden) "Photo and Electro Luminescence in Short Period Si/Ge Superlattice Structures"
10.20	*Coffee Break*
10.50- 11.30	**E.Molinari** (University of Modena, Italy) "Phonons in Short Period Si/Ge SL`s"
13.00	*Ski Race*
17.30	**Y.Shiraki** (University of Tokyo, Japan) "Luminescence Investigation on Strained SiGe/Si Modulated Quantum Well and Wire Structures"
18.15	**R.E.Slusher** (AT&T Bell Laboratories, USA) "Optical Processes in Microcavities"
19.00	*Closing*
19.15	*Farewell Party (Schloßschänke)*

Poster Sessions

1) Monday, Tuesday
2) Wednesday, Thursday

This winterschool is sponsored by the following institutions and companies:

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Dephasing and Inelastic Scattering by Coulomb Interactions in Mesoscopic Systems

Yoseph Imry

Dept of Condensed-Matter Physics
Weizmann Institute, Rehovot, 76100
Israel

A general formulation will be given of the loss of phase coherence between two partial waves, leading to the dephasing of their interference. This is due to inelastic scattering from the "environment" (which is a different set of degrees of freedom that the waves are coupled with. For a conduction electron, the other electrons.are often the dominant environment of this type. Coulomb interactions with the latter yields, especially at lower dimensions, the most important dephasing mechanism. It will be shown how this picture yields rather straightforwardly the results of Altshuler, Aronov and Khmelnitskii in 1 and 2 dimensions.

As a new application of the above ideas, the dephasing in a 0-dimensional quantum dot will be considered. This will lead to stringent conditions for observing the discrete spectrum of such a dot, in agreement with recent experiments. The crossover at low temperatures in small wires from one to zero-dimensional behavior will be shown to "rescue" the Landau Fermi-liquid theory from being violated because of the temperature to the 2/3 behavior of the 1D dephasing rate.

After clarifying generally the relationship between the e-e scattering rate and the dephasing rate, the connection with the former will be done in the ballistic regime.

This lecture is based on work with A.Stern, Y. Aharonov and U. Sivan.

INTERACTIONS IN THE TRANSPORT PROPERTIES OF NANOSTRUCTURES

B. Kramer, T. Brandes W. Häusler, K. Jauregui, D. Weinmann,

I. Institut für Theoretische Physik, Universität Hamburg, Jungiusstraße 9, D–20355 Hamburg

Interaction processes are of great importance for the understanding of the electronic transport properties of quantum coherent samples, although the conditions under which such a system can be considered as coherent depend strongly on the *absence* of phase breaking interaction processes. Among the many possibilities electron–phonon and electron–electron interactions are most important. In this contribution we will discuss three aspects which demonstrate some of the most striking features in connection with electron transport in sub–micron structures.

First, we consider the interaction of acoustic phonons with the electrons in a quasi–one dimensional quantum wire[1]. We will demonstrate that it is only above a certain critical Fermi velocity that the phonons can influence the electron states significantly. As a consequence, we predict a characteristic temperature dependence of the plateaus in the linear conductance as a function of a magnetic field which should be experimentally observable.

The Coulomb interaction between the electrons in a system that contains a quantum dot leads to rather sharp and regular resonance–like peaks in the linear conductance. When the mean distance between the electrons in the dot is comparable with the Bohr radius (usually of the order of 10 nm for AlGaAs based hetero–structures) the excitation spectrum of the interacting electrons shows fine structure which is related to the formation of a localized charge distribution, a Wigner molecule[2]. We demonstrate that the excitation spectrum can be understood in terms of vibrational and tunnelling modes. One experimental consequence is that the peaks in the linear conductance can split into multiplets.

Non–linear transport properties of interacting electrons in a quantum dot that is coupled to semi–infinite leads can be expected to yield more detailed information about the excitation spectrum. Using a Master Equation we present a detailed investigation for several models which include also the spin degree of freedom of the electrons[3 4]. We demostrate that the quantum mechanical correlations between the electrons lead to novel effects in the current voltage characteristics. Asymmetric conductance peaks occur due to asymmetries in the coupling. Negative differential resistances related to spin selection rules are predicted.

---

[1] T. Brandes and B. Kramer, to appear in *Solid State Communications* (1993)

[2] K. Jauregui, W. Häusler and B. Kramer, *Europhys. Lett.* **24**, 581 (1993)

[3] W. Häusler *et al.*, LT20 abstract, *Physica* **B**, in press

[4] D. Weinmann, W. Häusler, W. Pfaff, B. Kramer and U. Weiss, submitted to Europhys. Lett.

Transport spectroscopy on a single quantum dot in the non-linear regime

J. Weis, R.J. Haug, K. von Klitzing, and K. Ploog

In a quantum dot, electrons are confined by a three-dimensional potential, which leads to a discrete energy spectrum of electronic states. Coupling the quantum dot with two electron reservoirs by weak tunnel junctions allows to investigate electron transport through the quantum dot. At low bias voltage between the emitter and the collector reservoir and at low temperature, transport through the quantum dot is suppressed due to the energy required to an electron to the quasi-isolated quantum dot. This energy is mainly given by the Coulomb interaction and the effect is known as the Coulomb blockade of tunneling. By changing the electrostatic potential of a gate electrode, capacitively coupled to the quantum dot, this energy barrier can be overcome, allowing transport through the quantum dot. Within this transport regime, the number of electrons in the quantum dot can change only by one at a time. This is called the regime of single-electron tunneling. By changing the gate voltage further, the transport is blocked again having increased the number of electrons in the quantum dot by one.

After an introduction to the basic effect, transport measurements through a quantum dot defined by split-gates on top of a GaAs/AlGaAs heterostructure with a two-dimensional electron gas will be presented. The differential conductance was measured as a function of the bias voltage *and* the voltage of a gate electrode. Within the single-electron-tunneling regime, additional transport channels through the quantum dot are opened at increased bias voltage. Due to the measurement technique they can be classified by their opening condition being in resonance with the Fermi level of the emitter or with the Fermi level of the collector. Additional transport channels in the single-electron tunneling regime indicate that excited states of the electron system in the quantum dot become accessible for transport. Measuring the difference in the gate voltage between two resonances allows spectroscopy of the differences in transition energies between states of an N- and (N+1)- electron system in the quantum dot.

Features in the experimental data show that transport occurring via transitions between the groundstates of the N- and the (N+1)-electron system in the quantum dot can be suppressed by the occupation of excited states. Within the regime of single-electron tunneling, negative differential conductance occurs. Both features are explained by the occupation of excited states with 'long' lifetimes.

Applying a magnetic field to the quantum dot system changes the energy spectrum by modifying the electronic states in the quantum dot. For a magnetic field orientated parallel to the plane of the disc-like quantum dot, the spectroscopy at vanishing and at finite bias voltage will be presented. To interpret the shift of the gate voltage for opening a tranport channel, one has to take into account the fact that the magnetic field affects not only the electronic states of the quantum dot but also the electronic states of the gate electrodes and the leads to the quantum dot.

RESONANT TUNNELLING INTO QUANTISED DOTS AND WIRES: PITFALLS AND PROGRESS

J. Wang, P. H. Beton, N. Mori, T. J. Foster, A. K. Geim, M. Henini, N. La Scala Jr., P. C. Main and L. Eaves
Department of Physics, University of Nottingham, Nottingham NG2 7RD, U.K.

The talk describes a novel fabrication technique for producing sub-micron double barrier resonant tunnelling diodes based on optical lithography and selective wet etching. Resonant cavities in the form of quantum dots and wires can be made with electrically active dimensions down to 50 nm. By measuring the resonant tunnelling current in high magnetic fields applied perpendicular to the barrier interface, we can unambiguously identify lateral quantisation by observing the transition from electrically-quantised to magnetically-quantised states. A magnetic field parallel to the interfaces varies the overlap between laterally quantised states in the emitter and quantum well. We can then observe a series of peaks corresponding to tunnelling into the twenty lowest laterally quantised states of the quantum well. The I(V) characteristics can be modelled accurately within the effective mass approximation using a parabolic potential for the lateral confinement.

In addition, we have investigated a range of resonant tunnelling devices with different lateral dimensions and fabricated from different wafers. We show that peaks appear in the I(V) characteristics due to impurity-related mesoscopic tunnelling effects. Care is needed not to confuse this quite general phenomenon with lateral quantisation and Coulomb blockade effects.

Abstract of invited talk by L. Eaves
Mauterndorf Winterschool, February 1994

LOW-DIMENSIONAL RESONANT TUNNELING AND COULOMB BLOCKADE: A COMPARISON OF FABRICATED VERSUS IMPURITY CONFINEMENT

M. A. Reed, M. R. Deshpande, E. S. Hornbeck, N. H. Dekker, and P. Kozodoy

Yale University

New Haven, CT 06520 USA

Nanometer scale fabrication techniques, combined with epitaxial resonant tunneling structures, now routinely allow the study of quasi-0D confined electron systems. In addition to energy level separations that are tunable by the confining potentials, these systems can also exhibit Coulomb blockade. We have fabricated a series of novel InGaAs "vertical" quantum dots which are specifically designed to allow (and indeed exhibit) an interplay between dimensional quantized levels and Coulomb blockade levels. Spectroscopy is presented which distinguishes between the effects. Additional finer structure is observed, and is interpreted as due to irregularities in either the surface potential or dopant profile.

Suprisingly similar I(V) and G(V) characteristics have previously been reported for larger, confined resonant tunneling devices. We have found that some characteristics exist regardless of the lateral confinement, and that the turnon characteristics of nearly all resonant tunneling devices exhibit sharp peaks in conductance. These have previously been attributed to lateral confinement; we show that instead these are attributable to tunneling through single quantum well donor states. We have performed electronic spectroscopy of these states, and find binding energies as large as 10-20 meV greater than expected for a single quantum well donor, with corresponding intrinsic linewidths ~0.5 meV. These unintentional donor states are distributed in energy, dependent on both donor position in the quantum well and quantum well width fluctuations. These states also exhibit finer structure, and a comparison of these versus fabrication-confined structures will be presented.

8th International Winter School
Mauterndorf, Austria, February 1994

THEORY OF SINGLE-ELECTRON DEVICES

Konstantin K. LIKHAREV
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Stony Brook NY 11794-3800, U.S.A.

In the past few years a new field of physical and applied electronics (commonly nicknamed single-electronics) has emerged. The physical background of this field is formed by effects of correlated tunneling, which were predicted theoretically in the mid-1980s. Virtually all these predictions have been confirmed during the period 1987-93 in experiments with normal-metal, superconductor, and semiconductor junctions and systems.

Physically, the effects correlated tunneling results from charging of small but macroscopic conductors by single electrons (Cooper pairs), which affects low-temperature transport between the conductors. Practically, these effects enable one to control motion of single electrons and/or Cooper pairs in solid state circuits. Preliminary analyses have shown that single-electronics may yield a completely new generation of digital and analog devices with unparalleled performance. Most notably, this approach may allow implementation of extremely dense digital circuits with up to 10^{11} active devices (logic gates and memory cells) per square centimeter. However, in order to use this remarkable opportunity, numerous problems should be solved.

The goal of this talk is to give a brief review of the background physics of the single-electron devices, and then concentrate on their theory, including the quasiclassical (so-called "Orthodox") approach and its extensions to multi-particle tunneling and few-electron systems with discrete energy spectrum. I will also describe theoretical predictions of possible performance of various analog and digital single-electronic devices. In conclusion, the most urgent problems of this new exciting field will be discussed.

References:

1. K.K. Likharev, IBM J. Res. Devel. **32** (1987) 144.
2. D.V. Averin and K.K. Likharev, in: *Mesoscopic Phenomena in Solids*, ed. by B. Altshuler *et al.* (Elsevier, Amsterdam, 1991), Chapter 6.
3. *Single Charge Tunneling*, ed. by H. Grabert and M. Devoret (Plenum, NY, 1992).

Chaotic Transport and Fractal Spectra in Lateral Superlattices

T. Geisel, R. Fleischmann, R. Ketzmerick, and G. Petschel

Institut für Theoretische Physik und SFB Nichtlineare Dynamik
Universität Frankfurt, D-60054 Frankfurt am Main, FRG

As the trend to smaller and faster microstructures progresses, understanding the nonlinear dynamics of few electrons in anharmonic potentials becomes increasingly important. At the present stage where the Fermi wavelength is still smaller than typical spatial scales much of the dynamics can be described by (chaotic) classical trajectories, but in the future quantum mechanical treatments in the semiclassical regime will be required.

The talk will give an overview on recent work on applications of nonlinear dynamics to antidot lattices and will demonstrate how fundamental concepts like the KAM-theorem are manifested in recent experimental results. In particular it was shown that Weiss' magnetoresistance oscillations can be explained entirely by chaotic trajectories, as regular trajectories remain pinned in an electric field due to the KAM-theorem. The negative Hall effect in antidot lattices was explained by chaotic channeling trajectories moving in opposite direction to the Lorentz force. Similarly the occurrence of several nonquantized Hall plateaus in ballistic microjunctions were explained by nonlinear dynamics.[1]

A quantum mechanical description has to tackle the problem of Bloch electrons in magnetic fields. In the framework of Harper's equation it was shown that the dynamics of wavepackets exhibits an unususal diffusive spread and that correlation functions decay extremely slowly in the form of a power law. Both properties can be related to multifractal properties of the energy spectrum. The influence of classical chaos on such a spectrum was studied in a newly developed realistic model which was derived without any approximations from the most general single-particle Hamiltonian. It thus overcomes the serious failures of Harper's equation for lateral superlattices and lends itself to applications in experimental situations.[2]

1. R. Fleischmann, T. Geisel, R. Ketzmerick, Phys. Rev. Lett. 68, 1367 (1992) and Europhys. Lett., in press;
   T. Geisel, R. Ketzmerick, O. Schedletzky, Phys. Rev. Lett. 69, 1680 (1992).
2. T. Geisel, R. Ketzmerick, G. Petschel, Phys. Rev. Lett. 66, 1651 (1991) and 69, 695 (1992);
   G. Petschel, T. Geisel, Phys. Rev. Lett. 71, 239 (1993).

Wannier-Stark Effect in Superlattices

C. Hamaguchi, M. Yamaguchi, M. Morifuji, K. Taniguchi, H. Kubo, C. Gmachl[†] and E. Gornik[†]

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In a superlattice with thinner barrier layers the electron wave functions will penetrate in the barrier layers and form minibands, resulting in wavevector dependent energy states in the direction parallel to the superlattice direction. On the other hands, when a high electric field is applied to such a superlattice, electrons and holes are localized in a well region and form discrete energy levels called Stark-ladders, which is known as the Wannier-Stark effect. The modulation spectroscopy, such as electroreflectance method, is known to be a precision method to obatain the optical transitions. In the present work we used the electroreflectance method and investigated the optical transitions in higher photon energy region in addition to the region near the fundamental absorption edge. We found that the transition energies are well expressed by $E_{jm} = E_j + meFd$, where F is the electric field, E_j is the transition energy without electric field, $m = 0, \pm 1, \pm 2, ...$, and d is the superlattice period. Such behavior of transition energies well indicates the existence of Stark-ladders. One may expect that the energy band structure of a superlattice in an electric field can be obtained by including the electric field in band theories. This is easily done by using the tight-binding method, although the tight-binding matrix becomes very large, where we are not able to use the cyclic boundary conditions due to the lack of the translational symmetry. We will show the results obtained by the tight-binding method in finite superlattice periods and demonstrate that the method is very useful to interpret the optical transitions. In photon energy region 1.5 – 1.9 eV, we compared the experimental results with the tight-binding calculation and found a good agreement. In addition, observed anti-cross behavior of signals is interpreted in terms of a generation of bonding- and anti-bonding states due to mixing between neighboring localized states. In addition, we have observed signals in higher photon energy region (1.9 – 2.2 eV). These signals suggest the localization of states which have energies higher than the AlGaAs barrier, althogh there were no reports on the localization of such above barrier states. From the tight-binding calculation, we found that the spin-orbit split off (SO) states are also localized at high electric fields, and that the transition matrix elements between the localized SO states and the conduction states are large enough to be observed with optical measurements. Thus the transitions at higher photon energy arise from the localized state in the spin-orbit split off band.

Spectroscopy on Field-Effect Defined Quantum Wires

W. Hansen, A. Schmeller, H. Drexler, and J. P. Kotthaus
Sektion Physik, Ludwig-Maximilians-Universität, 80539 München

The lecture will review a number of experiments, in which the properties of high mobility electronic systems in strong lateral potential superlattices are studied. A special technique to measure the far-infrared (FIR) absorption allows for the study of one-dimensional intersubband resonances in an electron quantum wire with only one subband occupied. If the lateral potential superlattice is imposed on a quantum well we observe strong Franz-Keldysh oscillations in the infrared (IR) absorption spectrum.

The electronic systems are generated in special heterojunction devices in which intentional doping in the vicinity of the electron system under investigation is avoided. The potential superlattice is field-effect induced by means of dual gate techniques. Thus process induced damages are avoided, the confinement potential is not affected by impurity potentials from intentional dopants and the potential superlattice is tunable during the experiments.

The one-dimensional subband onsets of electron quantum wires are clearly reflected in the capacitance spectroscopy. Whereas in previous measurements the modulation of the capacitance signal has only been resolved with derivative techniques we now are able to clearly resolve the subband onsets in the direct capacitance signal. The measurements allow for studies of the electronic system in the one-dimensional quantum limit that is of particular fundamental interest. Fine structure in the capacitance signal reflects the rapid renormalization of the effective confinement potential at very low electron densities.

The capacitance technique also enables us to perform FIR absorption spectroscopy of very small systems. The resonantly absorbed FIR causes a change of the capacitance signal recorded as function of the magnetic field or gate voltage. Experiments will be discussed in which FIR absorption is studied in quantum wire systems that are in the one-dimensional quantum limit.

The strength and quality of the superlattice potential is furthermore demonstrated in measurements of the absorption of IR radiation at energies close to the effective bandgap of the quantum well. Interdigitated gates allow us to study the IR absorption in quantum wells in the presence of lateral fields with a strength of about 100kV/cm. Correspondingly, exciton dissociation is observed in the luminescence and the absorption spectra reveal clear signatures of the Franz-Keldysh effect. A strong negative differential resistance between the fingers of the interdigital gate promises for potential device applications.

Optical Spectroscopy on Quantum Wells and Tunnel Structures under Conservation of Angular Momentum

G. Hendorfer

Institut für Experimentalphysik, Johannes-Kepler-Universität Linz

The electronic states of confined electrons and holes in nearly lattice matched quantum wells are determined essentially by the basic QW parameters as width and barrier height. In lattice mismatched structures, the influence of strain on the band structure offers an additional degree of freedom for tailoring electrical and optical properties and thus to meet specific device requirements. In this case, however, confinement and strain affects the subband structures, and the assessment via excitonic peaks in absorbtion or photoluminescence excitation is less straightforward. In particular, discrimination between heavy-hole and light-hole excitons can be very difficult and reliable assignments can rarely be obtained by comparison with model calculation alone.

We show that by using circularly polarized light in photoluminescence and excitation luminescence spectroscopy one can overcome these difficulties: the observed excitonic peaks can be identified unambiguously. Reliable assignment of the observed peaks is necessary if the band offsets are to be determined. In particular, the difference between the energy of the e_ih_1 and e_il_1-transitions in wide quantum wells (where confinement effects can be neglected) is very important since it yields the strain induced splitting of the valence band. In pseudomorphic structures like InGaAs/GaAs or InGaAs/AlGaAs this difference in energy can be used to determine the In mole fraction. We show that this technique yields better accuracy for the In mole fraction than conventional photoluminescence.

If a transverse magnetic field is applied to the sample the degree of circular polarisation of the photoluminescence is reduced until the inverse precession frequency of the electron spins becomes smaller than the corresponding spin lifetime. From such an experiment the spin lifetime of confined excitons can be determined. The spin lifetime decreases strongly with decreasing well width because of the detrimental effect of imperfect interfaces.

Finally, we also demonstrate the optical detection of tunneling in excitation luminescence experiments. The spin conservation during the tunneling process allows to investigate inelastic tunneling processes in thick barriers.

One-dimensional excitonic recombination kinetics and intersubband relaxation

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The modification of carrier thermalization and recombination kinetics in quasi one-dimensional systems (quantum wire, QWR) with respect to two-dimensional systems (quantum well, QWL) are debated controversely and experimental work is scarce so far except first fundamental results [1]. Here we report a systematic investigation of the carrier capture, carrier cooling, intersubband relaxation and interband recombination in semiconductor quantum wires. The temperature dependence of radiative lifetimes and intersubband scattering time constants is reported for the first time and will be discussed under consideration of the "phonon-bottleneck" effect.

The results are obtained from single AlGaAs/GaAs quantum wires grown on non-planar substrate [2], investigated by means of spectrally, spatially and time-resolved photo- and cathodoluminescence as a function of temperature and excitation density. The generated carrier densities vary from the low excitation limit ($n*a_0<<1$) up to high excitation conditions $n*a_0\sim1$ inducing the population of higher subbands. The *in-situ* fabrication of the wires by organo-metallic vapor phase epitaxy leads to defect free interfaces and high luminescence efficiency by eliminating the dominance of non-radiative recombination [1]. In a wide temperature range the intrinsic radiative recombination properties can thus be studied. Up to 200K the recombination kinetics is dominated by radiative processes.

A variety of spectral features can be identified: At low excitiation levels the (e,hh),n=1 groundstate dominates the emission spectrum. Its peak position exhibits a variation of some meV along the wire due to inhomogeneties which are directly imaged by cathodoluminescence. With increasing excitation density the groundstate gets filled and its luminescence intensity strongly saturates. The higher one-dimensional subbands caused by the lateral confinement are increasingly populated and finally the n=2 transition (The separation from n=1 is ΔE=23meV, which is less than the LO phonon energy) dominates the spectrum. Such a population of these and even higher subbands is observed with increasing temperature as well.

In time-resolved measurements the capture of carriers from the barrier into the quantum wells and wire and subsequent filling of the QWR levels is directly observed. The depopulation of the n=1 groundstate is governed by radiative recombination of the charge carriers. The lifetime is found to be 500ps at 5K. With increasing temperature this lifetime increases up to 2ns at 100K and 3ns at 200K. These are the longest recombination time constants ever reported for quantum wire structures. The n=2 subband has two relaxation channels: radiative recombination and the n=2 to n=1 intersubband relaxation which can take place only when empty states in the n=1 levels are available. Accordingly the groundstate is pumped by a highly populated n=2 level and its transient shows a delayed onset. A rate equation model taking into account these effects allows a quantitative fit of the transients. Temperature and carrier density dependent lifetimes and scattering rates are obtained. A comprehensive interpretation of the inter- and intrasubband relaxation, i.e. thermalization in k-space and real-space, of quasi 1D carriers is given for the first time.

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Inelastic Light Scattering in the Integral and

Fractional Quantum Hall Regimes

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Gap excitations of the fractional quantum Hall effect have been observed by resonant inelastic light scattering[1]. These results are a vivid example of unique applications of the light scattering method in studies of electron-electron interactions in electron systems of semiconductor quantum structures. Such applications of resonant light scattering are based on the capability to measure spin-density and charge-density collective modes and also excitations that are not predicted by conventional response functions of the electron gas. This lecture presents recent studies in the integral and fractional quantum Hall regime. The mechanisms of resonant inelastic light scattering by the electron gas are also evaluated for their impact in studies of many-body interactions.

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Theory of the half-filled Landau level

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A recent theory[1] of a compressible Fermi liquid-like state at Landau level filling factors $\nu = 1/q$ or $1 - 1/q$, q even, is reviewed. The approach was a transformation that represents each electron as a fermion attached to a δ-function flux of size $q\Phi_0$ (with q even). The attached flux can be represented as a coupling of the fermions to a gauge field whose action is the (abelian) Chern-Simons term. In a mean field approximation where the Chern-Simons gauge field is replaced by its spatial average (on the assumption that the fermions form a state of uniform density) the fermions see a net magnetic field of zero, if the filling factor for the electrons is $1/q$ and the sign of the attached flux is chosen appropriately. The fermions may then form a Fermi sea, which is a compressible state. The excitations are thus fermions near a Fermi surface, but experience long-range gauge interactions. In more physical terms, a fermion (quasiparticle) is a bound state of an electron and q vortices in the fluid of the remaining electrons. If the filling factor differs from $1/q$, the fermions see a net field, and at filling factors $\nu = p/(qp+1)$ they may fill $|p|$ Landau levels, which is Jain's construction[2] of the incompressible quantized Hall states. The role of fluctuations in the gauge field in the compressible state will be discussed and may lead to behaviour similar to a "marginal Fermi liquid" or "Luttinger liquid". Recent experiments and numerical studies that appear to confirm predictions of the theory will be discussed, as will open questions.

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The Fractional Quantum Hall Effect in a New Light

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The picture that has emerged for the fractional quantum Hall effect (FQHE) during the past decade or so can be summarized in the following way: At low temperatures and in high magnetic fields 2D electron systems, under the influence of the dominating electron-electron interaction, condense into a sequence of quantum liquids at filling factor $\nu = p/q$ with q always odd (disregarding spin effects). The most prominent of these liquids exist at filling factor $\nu = 1/q$, approximated extraordinarily well by Laughlin's wavefunctions. A gap exists above this ground state and quasiparticle excitations across the gap carry a fractional charge. Deviation of the magnetic field from exact filling of one of the prominent states generates quasiparticles which, themselves, can condense into liquids of quasiparticles. This process can be repeated successively, thereby creating the hierarchy of all FQHE states at $\nu = p/q$ (once electron-hole symmetry and translation to higher Landau levels are included.)

Theoretical work of the past few years has cast a new light on the FQHE. While eventually this new picture may turn out to be equivalent to the traditional scenario, it offers a fresh view from a different angle on this intriguing electronic state. In this model, most strongly put forward by Jain, electron-electron interaction forces an even number of flux quanta onto each electron in a high magnetic field. The resulting new particles, consisting of electron and flux quanta, are appropriately termed composite fermions. In the presence of a residual magnetic field (deviation from an exactly even number of flux quanta per electron), the energy spectrum of the composites develops "Landau levels". The liquids of the FQHE then coincide with exact integer filling of these "Landau levels" of composite fermions. Recent theoretical studies by Halperin, Read and Lee associate a definite mass (about ten times the GaAs mass) with the composites and describe the states at *even-denominator* filling as being a Fermi sea of composite fermions with a well-defined Fermi wavevector, largely equivalent to the state at *zero magnetic field.*

This talk will present experimental data of the past few years which support this intriguing new picture of the FQHE as well as the behavior at even-denominators. It culminates with experimental data which show that the trajectories of these bizarre composite fermions find a description in terms of semi-classical physics.

Condensation of Indirect Excitons in AlAs/GaAs Coupled Quantum Well Structures

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In the present contribution we report about optical experiments on electric field tuneable AlAs/GaAs coupled quantum well (CQW) structures. In this system an electric field induced Γ-X transition can be obtained, in which the direct exciton in the GaAs QW is transferred into a real- and k-space indirect exciton with the electronic part of the wave function in the AlAs layer at the X-point. This transition causes a huge increase of the exciton lifetime (up to a factor of 1000), which is the basis for the new physical phenomena discussed in this contribution.

In a first part we intend to demonstrate the unique possibilities of CQWs arising from electric tunability. We concentrate thereby to the regime of small Γ-X separations (<30meV). Using the energetically tuneable X-point state in the AlAs layer as an internal energy spectrometer we are able to map out the local electronic density of states in the neighbouring GaAs QW in great detail. Performing spatially resolved and bias voltage dependent PL experiments we are able to resolve the unavoidable well width fluctuations of the GaAs QW as sets of discrete lines originating from highly perfect natural quantum dots.

In the second part we report on low temperature cw and time resolved magneto-optic experiments (T>350mK, B<15T) in the purely indirect regime, designed to search for theoretically expected condensation phenomena of indirect excitons. The lifetime in our system is long enough to allow for a thermalization of the indirect excitons down to temperatures below 1K. The perpendicular magnetic field increases the exciton binding energy and suppresses the kinetic energy of the excitons which results in an increase of T_C, the critical temperature for condensation. Our experiments are performed in a low density limit. The excitons can be regarded as rigid Bose particles and condensation phenomena are expected to be analogous to the Bose-Einstein condensation of excitons. Experimentally we find evidence for condensation in form of huge broad band noise in the photoluminescence intensity and in form of strong anomalies in the exciton transport. As a function of exciton density and temperature the described phenomena are only observed within certain phase boundaries.

OPTICAL STUDIES ON II-VI COMPOUND QUANTUM WIRES AND BOXES

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In this paper we review some recent optical studies on II-VI compound nanostructures fabricated either by etching 2 dimensional (2D) structures or by direct epitaxial growth.

Electron beam lithography and Ar ion beam etching have been used to fabricate quantum wires and boxes from 2D CdTe/ZnTe quantum wells grown by molecular beam epitaxy, with lateral sizes down to 40 nm and 70 nm, respectively. At low temperature, the photoluminescence (PL) intensity of these free standing nanostructures is comparable to that of the initial 2D quantum wells. However, the radiative decay is now dominated by the recombination of exciton trapped at defects/impurities localized in the nanostructures. This trapping mechanism is particularly efficient since it allows the observation of PL even in the smallest fabricated wires (40 nm). Electrodynamic effects in gratings of wires have also been investigated. The most remarkable result is the strong variation of both the PL intensity (by a factor of 4) and polarization (by a factor of 2) which occurs for grating periods of about the excitation and emission wavelength (0.5-0.8 μm).

Recently, ZnTe nanostructures embedded in CdTe matrix have been successfully grown by molecular beam epitaxy. ZnTe islands of one monolayer height and various lateral sizes are obtained by controlling the growth of ZnTe submonolayer on either flat (001) or tilted substrate surfaces. The reflectance spectrum exhibits numerous sharp structures which can be attributed to exciton localization on islands of different sizes.

PICOSECOND AND FEMTOSECOND SPECTROSCOPY OF HIGHLY EXCITED CHARGE CARRIERS IN SEMICONDUCTORS: THEORY

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Abstract. Time-resolved luminescence, absorption and four-wave-mixing spectroscopy in the picosecond and femtosecond regime are presently the most efficient experimental methods for studying energy and phase relaxation rates of highly excited charge carriers in solids. Here most of the effort concerns semiconductors, as these relaxation rates will determine and limit the efficiency of future generations of ultrafast electronic and opto-electronic devices. The following survey describes some attempts at a detailed analysis of recent experimental luminescence and absorption data covering a representative range of materials, spectral regimes and excitation densities. In spite of the fact that nanostructures are at the focus of present-day technological developments our discussion is mainly limited to experiments on unstructured semiconductors, because the much simpler electronic structure of bulk materials will make it easier to realize the essentials of an extremely transient generation and relaxation dynamics of charge carriers and its description by appropriate Monte-Carlo or quantum-transport techniques.

Femtosecond Laser Excitation of Semiconductors

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As semiconductor devices get smaller, they invariably become faster. In spite of many years of research on transport in semiconductors, a sizable fraction of the interaction parameters for the electron-phonon and carrier-carrier interactions are not well known. One problem is that these parameters are significant more in kinetic processes rather than equilibrium processes. As a result, the study of semiconductor carriers excited by femtosecond laser excitation has proven to be one of the most effective methods of characterization of semiconductors as well as providing a probe for new physical effects. On the femtosecond time scale, however, it is not expected that the semi-classical Boltzmann equation will be correct, and a more basic quantum mechanical formulation is required. In this talk, the formulation of equivalent transport equations from the Schrödinger equation and its variants will be briefly reviewed, to show how a Boltzmann limit may be reached. Equations on the fs time scale involve the presence of the transient polarization as well, and the higher order interactions of this process are shown to be connected with equivalent many-body effects in nanostructures and mesoscopic systems. Results, using an ensemble Monte Carlo method, for electron-electron and electron-phonon interactions will be presented to show how these studies can be used to investigate the strength of the electron-phonon interaction and how the finite collision duration affects such studies.

END

Coherent Dynamics of Exciton Wave Packets

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Coherent nonlinear optical experiments with sub-picosecond time-resolution allow the investigation of several important physical properties of nanostructures, which cannot be studied with linear optical methods. In particular, time-resolved four-wave mixing experiments have become a powerful tool providing an experimental access to ultrafast phenomena in low-dimensional structures. By using ultrashort pulses for optical excitation, spectrally adjacent excitonic transitions can be excited simultaneously, i.e., excitonic non-eigenstates can be created. As a consequence, the coherent nonlinear optical response exhibits characteristic temporal modulations (quantum beats).

Such quantum beat experiments provide access to homogeneous excitonic linewidths, to coupling effects between distinct optical transitions, and allow the determination of small spectral spacings between distinct excitonic transitions irrespectively of inhomogeneous broadening effects, which are unavoidable in nanostructured semiconductor materials. In particular, the analysis of the temporal development of excitonic wave packets represents a simple way to precisely determine the exciton binding energy in quantum well structures. In addition, mixing of electronic and excitonic states induced by disorder potentials can be studied quantitatively. Another important application of these sub-picosecond coherent experiments is to study the field-induced coherent dynamics of optically created wave packets, e.g., carrier escape tunneling out of electrically biased quantum wells.

We will discuss several sub-picosecond quantum beat experiments performed on various semiconductor heterostructures in order to demonstrate that this nonlinear optical technique helps to better understand the electronic and optical properties of nanostructures.

Terahertz - Blochoscillations in Semiconductor Superlattices

Prof. H. Kurz - Institut of Semiconductor Electronics, RWTH Aachen

The coherent dynamic of electronic wavepackets in semiconductor nanostructures has recently been attracting considerable scientific interest. Steady progress in MBE-technology in fabricating AlGasAl/GaAs superlattices with nearly atomically smooth interfaces opened the way to novel physical effects, like Wannier-Stark-ladders (WSL) and Bloch-oscillations (BO).

The coherent optical excitation of several Wannier-Stark states in these superlattices by an ultrashort laser pulse induces a coherent motion of electronic wavepackets as revealed in recent degenerate four wave mixing experiments (1). The definite answer to the question whether this wavepacket performs a breathing or oscillatory motion is given by the observation of THz-emission from superlattices excited with femtosecond laser pulses (2). The frequency of this THz-radiation can be tuned by electrical fields as expected by the simple picture of Bloch-oscillations predicted by Esaki and Tsu (3). THz-emission from Bloch-oscillations can be observed up to 200 K.

In this paper the most recent experiments on THz-emission are presented and related to data obtained in time resolved optical experiments. By time resolved electro-optic sampling in transmission mode the oscillation of the wavepacket can be directly monitored, while in degenerate four wave mixing experiments more details on the superpositon of Wannier-Stark states are derived.Finally the prospects for THz-emission by Bloch-oscillations at room temperature are discussed.

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Bloch- and localized electrons in semiconductor superlattices

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Electrons in semiconductor superlattices represent a fascinating model system to study many key issues of solid state physics. The artificial periodicity gives rise to the formation of a quasi one-dimensional miniband structure, containing Bloch-like electrons. At the lower edge of each miniband, impurity bands are formed, which can be traced back to the hydrogenic donor levels in the low-doping limit. These impurity bands contain mainly localized electron states.

We have studied the optical properties of conduction electrons in n-type GaAs/AlGaAs superlattices. The relevant spectral range is the mid- to far-infrared, corresponding to inter- and intra-miniband excitations, respectively, for superlattices with a period of the order of 100 Å.

Starting from the measurement of the inter-miniband absorption, which clearly reveals the van Hove singularities at the edges of the superlattice Brillouin zone, we will discuss such issues as oscillator strengths, sum rules, and half-filled and completely filled bands, respectively. We will show that, in order to understand the inter-miniband absorption, it is necessary to also account for intra-miniband Drude-like absorption.

The competition between miniband and impurity absorption can be used to study the metal-insulator transition, which could be different than in bulk semiconductors, since in superlattices, layer thickness fluctuations provide an additional source for Anderson localization.

Finally, we will mention some future prospects for measuring the infrared response of electrons under the conditions of Bloch oscillations and Wannier-Stark ladders.

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LIGHT SCATTERING FROM OPTICAL PHONONS AS A LOCAL INTERFACE PROBE OF Si/Ge SUPERLATTICES

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The study of optical phonons as local probes of the interface structure has proved to be very useful in GaAs/AlAs superlattices (SL's), where it has provided much information on atomic scale intermixing [1]. The question of the degree of interface abruptness in Si/Ge superlattices is also becoming very important, in view of the recent promising results on their optical and transport properties and the consequent search for further improvement.

On the theoretical side, the full lattice dynamics of *intermixed* Si/Ge SL's has now become accessible from first principles in the whole three-dimensional Brillouin zone. Homogeneous strain, as well as local bond-length variations depending on the local atomic configurations in the intermixed regions, are accounted for through higher-order ab-initio interatomic force constants. By comparing phonon and Raman spectra calculated for different model intermixing profiles, we are able to identify the spectral features whose frequency or lineshape is most sensitive to the interface structure in various light-scattering configurations. The microscopic origin of such features is analysed by plotting the corresponding local density of vibrational states along the growth-direction or in the interface plane [2,3].

The results are used for the interpretation of recent experiments [2], obtained by means of a microprobe technique which gives access to both longitudinal and transverse polarizations. We show that the data are consistent with the picture of an intermixed alloy layer at the interfaces (≥2-3 monolayers in the best samples), and we are able to identify the character and spatial localization of the individual atomic clusters contributing to the vibrations. The possibility that Raman scattering in Si/Ge can be used to discriminate between different lateral scales of interface roughness (laterally homogeneous intermixing vs. long-range terrace-like corrugation) [3] is currently under investigation.

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Quantum magnetotransport and quantum chaos in antidot superlattices

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We present fully quantum-mechanical calculations of magnetotransport properties of antidot superlattices. Our calculations of the longitudinal and the Hall resistance are based on evaluating Kubo's formula for electrons in a quadratic antidot superlattice with a perpendicular magnetic field. To get the spectrum and the eigenfunctions we use the concept of magnetic Bloch functions[1]. Impurity scattering is considered according to Ando's self-consistent Born approximation (SCBA). Because all parameters, which characterize the antidot potential and the impurity scattering, are taken from the given experimental values, our calculations are parameter-free. The calculated results for the longitudinal and the Hall resistance are in quantitative agreement with experimental data[2] (see Fig.1). We find peaks in the longitudinal resistivity, which have been interpreted so far in the framework of classical nonlinear dynamics. The quenching of the Hall resistance at low magnetic fields is reproduced as well as the non-quantized Hall plateaus. The calculated density of states exhibits B-periodic oscillations, which have been found in semiclassical studies[3]. Furthermore the density of states also provides evidence for an enhanced cyclotron frequency. In addition we have evaluated the level statistics of the quantum spectrum and find level repulsion for low magnetic fields. With increasing magnetic field a soft transition to level clustering occurs, corresponding to the transition from chaotic to regular motion in the classical case.

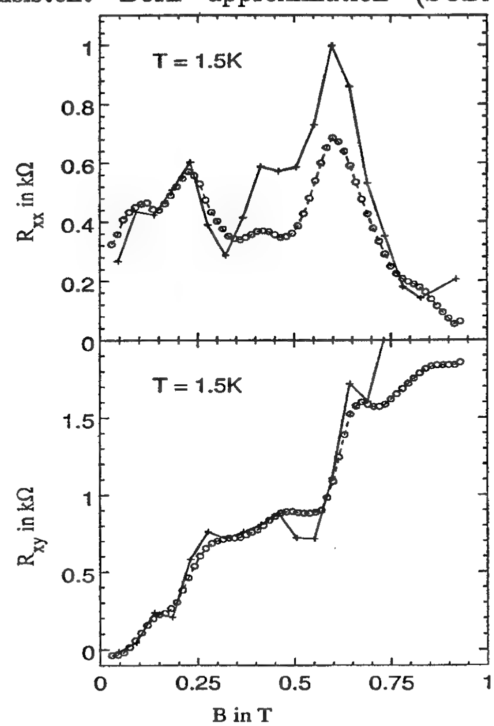

Fig.1 *Diagonal- and Hallresistance for a antidot superlattice. We have plotted calculated results (solid line) and experimental data (dotted line) from reference [2]*

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UHV/CVD GROWTH OF SI/SIGE HETEROSTRUCTURES AND THEIR APPLICATIONS.

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The era of SiGe HBT based integrated circuits arrived with the announcement[1] of a 12-bit Digital to Analog Converter fabricated using an analog optimization of IBM's SiGe HBT technology. Medium scale integration was employed, the circuit consisting of approximately 3000 transistors, and 2000 passive elements(resistor and capacitors). Operating at 1Ghz., this converter consumes approximately 0.75 watts, thus yielding power-delay performance a decade superior to prior devices. It is significant that this DAC was fabricated employing the same technology and toolset as found on a standard CMOS product line. In addition to the CMOS toolset, only one unique tool was utilized, a UHVCVD[2] system for SiGe deposition. The processing of these integrated circuits was in fact no different than that employed in fabricating high performance HEMT's[3], as well as the first N-type SiGe based RTD's[4], all functional and in fact optimized for operation at room temperature. It is therefore now possible to combine a waferscale manufacturable silicon-germanium based heterojunction technology with devices that utilize quantum phenomena, made accessible by the use of band offsets and strain induced band splitting in the Si/SiGe materials system. This new ability to incorporate leading edge developments in Si:Ge device physics into a standard technology line opens up a host of new areas for exploration.

In this talk, I will focus on recent advances in SiGe based science and technology, specifically exploring the state of the art in technological applications, as well as exploring new fundamental phenomena such as Transferred Electron Devices.

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Photo and Electroluminescence in Short-period Si/Ge Superlattice Structures

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Interband optical transitions have been studied in a variety of short-period Si/Ge superlattices structures by means of photocurrent spectroscopy, infrared absorption, photo (PL)- and electroluminescence (EL). Furthermore, the bandgap photoluminescence from strain-adjusted Si_mGe_n (m=9, 6, 3; n= 6, 4, 2) superlattices was studied under applied hydrostatic pressure. The strain-adjustment was achieved by a thick, step-graded $Si_{1-x}Ge_x$ buffer layer resulting in an improved quality of the superlattice with respect to dislocation density.

The onsets of the interband absorption in the energy range of 0.7 - 0.9 eV are in good agreement with the observed PL and EL, as well as with theoretical calculations. Bandgap-related EL was observed in mesa diodes at room temperature, whereas the PL disappeared at about 40K. In samples, annealed at growth temperatures (550°C) and higher, a systematic shift of the bandgap was observed which is discussed in terms of a process involving interdiffusion of the Si and Ge atoms. Photocurrent measurements at low temperatures support the model from PL studies suggesting that the photogenerated electrons are immobile in the SLS at low temperatures and have to be thermally ionized from shallow levels.

The hydrostatic-pressure-dependence was modelled using an approach based on deformation potentials and effective-mass theory.

Apart from the strain-symmetrized Si/Ge superlattices, another structure that has been proposed to act as an efficient, light-emitting device in the Si-based systems is an ultrathin Ge layer (1-2 monolayers) embedded in bulk Si. We report on the electroluminescence spectra at various temperatures from a sample based on this concept, namely a layer sequence consisting of 2 periods of $Si_{17}Ge_2$ grown pseudomorphically on an n^+ Si -substrate. A very intensive, well-resolved EL was obtained at 55K from the QW. The luminescence was observed, already at low current densities.

LASING IN LOWER DIMENSIONAL STRUCTURES FORMED BY CLEAVED EDGE OVERGROWTH

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We have used the molecular beam growth technique, we call Cleaved Edge Overgrowth[1] (CEO) to fabricate highly efficient lasers, which operate in the 1D quantum limit. The active region of our laser consists of quantum wires that form at the T–shaped intersections of two 7 nm wide GaAs quantum wells grown along the [001] and after an *in situ* cleave along the [110] crystal axis. These intersections are, in turn, embedded in a T–shaped dielectric waveguide, which confines the optical mode to the vicinity of the quantum wires.The origin of the 1D quantum mechanical bound state is the relaxation of quantum well confinement at this intersection which leads to an expansion of the electron and hole wavefunction into the larger available volume at the T–junction.

The high degree of structural perfection and the precise control and uniformity of the quantum wire dimensions achievable in this way allows the observation of stimulated optical emission from the lowest exciton state in optically pumped devices. It thus appears that these structures can serve as a model system to test the long standing predictions on the performance of 1D and 0D lasers.

The interpretation that the observed quantum wire response is exclusively due to exciton recombination is based on the near spectral constancy of the emission over almost 3 orders of magnitude in excitation power from low power luminescence to an intense single mode lasing line. The implied absence of band–gap renormalization effects suggests that the Mott density is never reached in the quantum wires and indicates interesting new behaviour for excitons in 1D. In contrast the quantum well photoluminescence peak indeed shifts to lower energies consistent with the notion that the 2D excitons ionize and a free electron–hole plasma forms.

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Optical Processes in Microcavities

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ABSTRACT

Optical microresonators can now be fabricated with dimensions of the order of a half wavelength on a side. For semiconductor microresonators this results in only a few optical modes interacting with emitting material in the cavity. In this limit the threshold lasing characteristics are dramatically modified. Semiconductor microdisk experiments will be described where as much as 20% of the spontaneous emission is captured into the single lasing mode. This strong coupling of the radiation field with the resonant mode can cause anomalous laser linewidths and fluctuation phenomena. These experiments provide a good test of detailed models of dense, nonequilibrium electron-hole gases. Extensions of optical microcavities to a broad range of material systems will also be discussed.

Luminescence Investigation on Strained SiGe/Si Modulated Quantum Well and Wire Structures

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One of the prominent features of SiGe/Si heterostructures is that the band structure is interestingly modified by changing the strain distribution in the heterostructures. Especially, the band gap is changed in different ways and the band alignment changes from type-1 to type-2 depending on the structure. This situation can be well studied from the luminescence measurements of QWs if their luminescence properties are good enough. There are several important issues concerning formation of highly luminescent SiGe materials. The first one is the critical thickness of the strained layers, that is, the maximum thickness where coherent epitaxial growth can take place. The second is the abruptness of the SiGe/Si heterointerface. Currently it is well recognized that the main cause to deteriorate the interface integrity is surface segregation. In the first part of this talk, what the surface segregation is and how it takes place are reviewed. After clarifying the mechanism of surface segregation, methodology to suppress it is discussed and a new technique, called segregant-assisted growth (SAG), where atoms having strong segregation tendency are introduced at heterointerfaces is proposed and its advantages are demonstrated, including infrared light absorption due to intersubband transition in the conduction band of extremely narrow type-2 QWs and band edge emissions from type-1 QWs. Gas source MBE (GSMBE), which is considered to be quasi-SAG and hydrogen generated at the growth front acts as a segregant, is revealed to provide high quality SiGe/Si heterostructures with abrupt interfaces. Highly efficient band edge emissions are observed in not only type-1 but also spatially indirect type-2 QWs grown by the quasi-SAG method. By exploiting the advantages of GSMBE, various kinds of QWs and also QWRs are fabricated and the systematic study on band modifications and carrier dynamics in modulated structures becomes possible. The most essential feature of QWs is the quantum confinement effect and it is confirmed from the luminescence blue-shift with the decrease in the well width. The ratio between no-phonon (NP) peak and its phonon replica (TO) is shown to well reflect the nature of QWs formed by alloy materials. The coupling of QWs, which is the simplest element of superlattices, is well understood based on effective mass approximation by precisely taking into account the band alignment. Comparison of photoluminescence and electroluminescence is useful to understand carrier dynamics in indirect band gap materials. QWRs are well fabricated on V-grooved patterned substrates using GSMBE and luminescent properties much different from those of QWs are observed, suggesting realization of lower dimensional systems in SiGe/Si heterostructures. These findings may indicate high potentials of SiGe/Si heterostrucutres not only in scientific areas but also in device applications.

8th International Winterschool on New Developments in Solid State Physics

"INTERACTION AND SCATTERING PHENOMENA IN NANOSTRUCTURES"

Mauterndorf, Salzburg, Austria
14 - 18 February, 1994

Organized by G. Bauer, H. Heinrich, F.Kuchar,
Solid State Physics Division of the Austrian Physical Society.

Location: Castle of Mauterndorf

Topics: novel techniques for nanostructure fabrication, nanostructure lasers, non-linear transport in nanostructures, physics of ballistic and single electron devices, electronic states in nanostructures, interaction effects and composite particles, ultra-fast optical and high-frequency phenomena.

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Registration: Deadline: Jan 15, 1994. Use the attached registration form.

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